Turning a Keen Eye on the Stars

By collecting starlight with widely spaced mirrors, astronomers are mapping the heavens with superlative precision. Soon they'll be turning those maps into images

On December 13, 1920, atop Mount Wilson in Southern California, the physicist Albert A. Michelson and his colleague F.G. Pease achieved an astronomical first by directly measuring the diameter of a star, the red supergiant Betelgeuse. By a technique called astronomical interferometry, they had briefly turned Mount Wilson's 100-inch telescope, then the world's largest, into the equivalent of a still-larger instrument. But the procedure—gathering starlight with two widely separated mirrors and precisely meshing its waves at the focus of the giant telescope—proved so painstaking that after a few more feats of measurement, they wrapped their apparatus in canvas and stored it away in the rafters of the telescope dome. Astronomical interferometry slipped into obscurity for decades.

Now interferometry is back in the tool kit of optical astronomers. The first of a new generation of interferometers are already racking up new diameter measurements of stars and stellar dust shells. They have teased apart close binary stars and determined key steps in the ladder of cosmic distances. And this summer, on Anderson Mesa in northern Arizona, the Naval Research Laboratory (NRL) and the U.S. Naval Observatory (USNO) will join forces to build the Big Optical Array (BOA), the first optical interferometer to turn these precision measurements into images—images of such high resolution that they could map surface features on other stars.

Michelson's technique first reemerged during the 1950s in a quite different venue, radio astronomy. But in the past 10 years, advances in sensors and control systems, together with a better understanding of the atmospheric turbulence that distorts light waves, have enabled optical astronomers to reclaim the technique. They are convinced, as BOA project manager Kurt Weiler of the NRL says, that "Michelson had the right idea—[he] was just 70 years too early."

Even the BOA will work on the same principles as Michelson and Pease's original interferometer, whose two collector mirrors were mounted at either end of a 20-foot girder suspended across the opening of the telescope. Other mirrors at the center of the girder directed starlight from the outboard mirrors into the telescope, where it was combined at the focus. By gathering light with mirrors 20 feet apart, the interferometer in effect gave the Mount Wilson 100-inch telescope the same ability to resolve fine details as a 240-inch instrument.

Delicate fringes. The secret of an interferometer's resolving power lies in the interference pattern created when light waves from the same point in the sky are collected by the separate mirrors and then recombined. The pattern consists of alternate bright and dark bands, or "fringes"—the bright fringes appearing where the waves in the separate beams are in step and reinforce each other, and the dark ones where the waves are out of synch and cancel each other out. The interference pattern yields information about the position or diameter of a star. In diameter measurements, for example, the collector mirrors are gradually moved apart, which decreases the contrast between the dark and light bands. When the fringes vanish, the instrument at last "sees" the star as a disk rather than a point. A geometric relation between the wavelength of the starlight and the separation of the mirrors then gives the star's angular diameter.

Large Scale Measurements

A Special Section of *Science*

The breadth of Earth and the depths of space can't be crammed into a laboratory for study. But by relying on satellites, telescopes, and unique instruments like optical arrays and gravitational-wave detectors, Earth and space scientists are managing to measure and map these expanses. The following news stories and articles showcase the latest techniques and results—and the new puzzles, demanding new stratagems, that they spawn.

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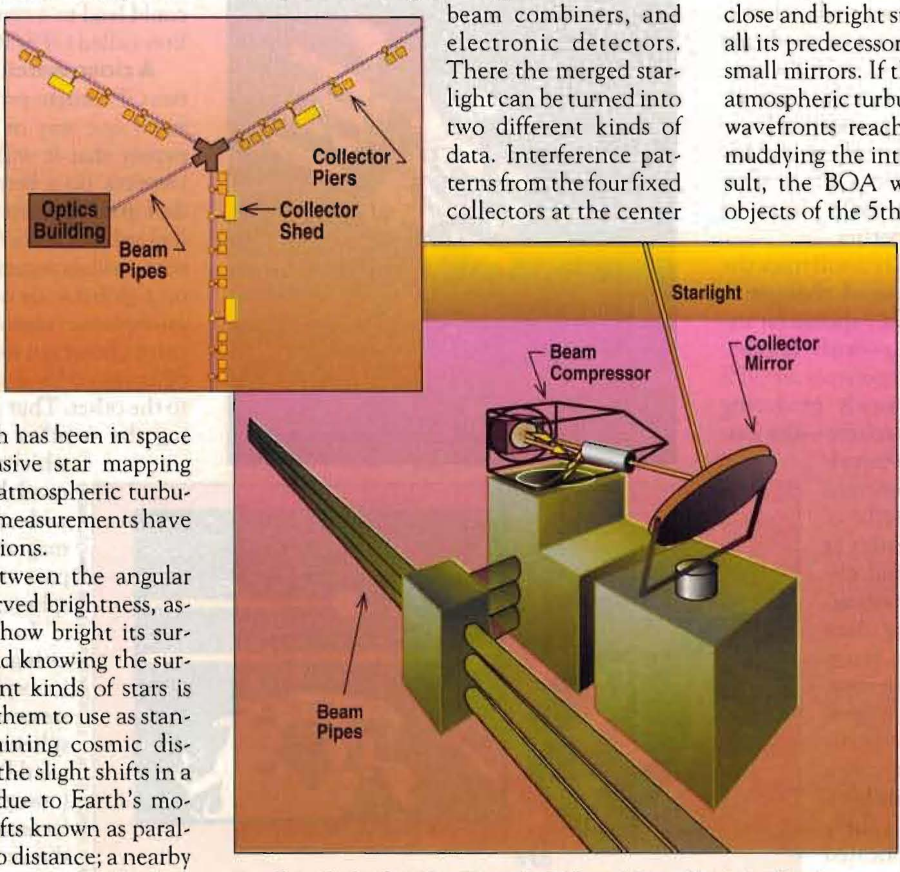
But the pattern can be vexingly hard to interpret, because it won't hold still. Turbulence in the atmosphere can distort the wavefronts of starlight, changing the relative timing of their arrival at the different mirrors. The tiniest wobble in the instrument itself can have the same effect, by altering the length of the paths the waves have to travel from mirrors to beam combiner. Because the position of each fringe is sensitive to the slightest change in the timing of the combined waves, the result of all this unsteadiness is that the fringes jiggle wildly and drift away. "It's like trying to read the newspaper through a bubbling aquarium while jumping on a waterbed," says Weiler.

That unsteadiness defeated Pease when he tried to expand the original Mount Wilson interferometer into a 50-foot version. And it defeated would-be imitators for decades while radio astronomers, who had the advantage of working with waves 100,000 times longer than visible light, made the most of it by linking their telescopes in interferometers spanning miles—like the Very Large Array in New Mexico—or even entire hemispheres—as in very long baseline interferometers.

To catch up, optical interferometry needed a way to tame the jiggles. A key breakthrough came in 1975, from a physics graduate student at the Massachusetts Institute of Technology named Michael Shao. Shao, now at the Jet Propulsion Laboratory (JPL), developed a means of introducing variable time delays into the beams. Shao's strategy is to send each beam through a "mechanical delay line": a set of movable mirrors mounted on rails, controlled by a system that monitors the brightest fringe in the interference pattern. As the fringe shifts due to turbulence and telescope wobble, the controller moves the delay-line mirrors by as little as a few tenths of a micron every hundredth of a second. The adjustments, by changing the distance the beam has to travel on its way to the combiner, delay it by just the right amount to cancel out the jiggles. The delay line also compensates for Earth's rotation, which would otherwise cause the fringes to drift, by moving the mirrors a steady millimeter per second.

Through the 1980s, Shao incorporated his mechanical delay line in a series of interferometers culminating in the Mark III, a set of mirrors on a 31-meter baseline near the Mount Wilson telescope where Michelson and Pease made their historic contributions. Meanwhile, astronomers at the University of Sydney and at the Observatoire de la Côte d'Azur in France have built interferometers with much longer baselines, relying on computers rather than a mechanical delay line to compensate for the jiggles. This alternative strategy leaves the fringes free to wander; later a computer processes the data, tracking and steadying each fringe after the fact.

These and other interferometers, by simulating conventional telescopes with apertures of tens or hundreds of meters, have opened the way to extraordinarily precise surveys of the sky. Take the Mark III, which is mapping the diameters and positions of stars with an accuracy about 20 times that of a conventional, single-mirror telescope. That matches the performance of the European Hipparcos satellite, which has been in space since 1989, doing extensive star mapping without the handicap of atmospheric turbulence. And those minute measurements have some large-scale implications.



Pooling their signals. The Big Optical Array will start with six collector mirrors arranged in a Y but may eventually include 10 collectors, dispersed along 250-meter arms.

SOURCE: USNO/NRL ILLUSTRATION: SUSAN NOWOSLAWSKI

From the relation between the angular size of a star and its observed brightness, astronomers can calculate how bright its surface must actually be. And knowing the surface brightness of different kinds of stars is helping astronomers put them to use as standard candles for determining cosmic distances. Measurements of the slight shifts in a star's apparent position due to Earth's motion around the sun—shifts known as parallax—can also give clues to distance; a nearby star is displaced more than a distant one.

Image maker. One thing these interferometers can't do is combine their beams to produce an image—something radio interferometers like the Very Large Array do routinely. To produce images, an interferometer needs at least three mirrors and elaborate computer processing of the merged beams. The BOA, scheduled to become the world's first imaging interferometer after it sees its first light next year, will go well beyond those basic requirements.

In its first incarnation, the BOA will include six half-meter collectors arranged in a Y. Four of the collectors will be fixed; two others will be movable, able to migrate as far as 35 meters out along the arms. The USNO-NRL team plans eventually to add four more movable collectors. Together, the movable collectors will act rather like a giant zoom lens. Set close in, they will provide a wide-angle view but sacrifice the finest detail; moved outward, they will yield a narrower field of view but higher resolution. The finest detail of all will emerge if the project receives additional funding and the arms of the Y are extended to 250 meters in length. That would give the BOA a resolution roughly 100 times better than a healed Hubble Space Telescope. With vision that keen, you could read a copy of this magazine in Boston from as far away as Washington D.C.

The starlight gathered by these far-flung mirrors will be piped down the array arms to an optics building housing the delay lines, beam combiners, and electronic detectors. There the merged starlight can be turned into two different kinds of data. Interference patterns from the four fixed collectors at the center of the array (which is separately dedicated as the USNO's Astrometric Optical Interferometer) will be used for long-term star mapping. Notes USNO astronomer Donald Hutter, technical manager of the project, "We will probably be charting the positions of 30 to 40 stars a night, and this would continue for some decades." At that rate, the observers will be able to return often to the same star in search of parallax, and they will also be able to keep watch for other slight wobbles that might signal the presence of a planet orbiting the star.

Fulfilling the BOA's mission of creating actual images will be a much slower process, involving all of its telescopes at once. In effect, a computer will "reconstruct" an enormously magnified image of the star from the interference patterns generated by every possible pair of mirrors in the array—a procedure that will take several hours for each image. "Data reduction will be a challenge," admits NRL astronomer David Mozurkewich, who is overseeing the imaging program. If it all works as planned, BOA images of other stars could reveal some of the same intimate details routinely observed on the sun: sunspots, the fine-scale pattern called granulation, and arches and streamers of gas in stellar atmospheres.

All that will only be possible for relatively close and bright stars, because the BOA, like all its predecessors, makes do with relatively small mirrors. If the mirrors get much larger, atmospheric turbulence starts to break up the wavefronts reaching individual collectors, muddying the interference patterns. As a result, the BOA will be limited to imaging objects of the 5th magnitude and brighter—about the same range of objects visible to the naked eye. To see the same kind of detail in faint, really distant objects—quasars and the hearts of other galaxies—astronomical interferometry will have to move into space. Outside the atmosphere, the mirrors can be as big as funding and NASA's launch capacities allow.

That potential did not go unnoticed by the Astronomy and Astrophysics Survey Committee, convened by the National Research Council to set priorities for astronomy during the 1990s. In its 1990 report, the committee strongly backed a NASA proposal for an Astrometric Interferometry Mission (AIM). A JPL design envisions AIM as an orbiting platform carrying three interferometers that could measure stellar positions with 100,000 times the precision of an ordinary ground-based telescope. European astronomers, meanwhile, are thinking of a complementary project: an imaging interferometer that would amount to a space-based version of the BOA. That's a brilliant future for a technique that once looked stillborn.

–Marcia Bartusiak

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